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A K-CELL injection system for SH-PermEBIT*

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In this paper, we report a newly developed Knudsen Cell injection system for SH-PermEBIT. This technique can overcome disadvantages of introducing organometallic gases and wired probes into EBIT and provide steady continuous injection. A specially designed vacuum line is used to ensure that the Knudsen Cell satisfies the vacuum level of SH-permEBIT. Using this system we successfully injected ytterbium into the SH-permEBIT and recorded a spectrum in the visible wavelength region.

Keywords: Knudsen Cell, EBIT, Metallic atom injection

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I. INTRODUCTION

Electron beam ion traps (EBITs) [1] are devices designed for studying the spectra of highly charged ions or their interactions with electrons. Unlike traditional EBITs which occupy large areas due to requirements on high electron beam energy and cryogenic operation, the Shanghai permanent magnet EBIT, SH-permEBIT [2, 3], has its specific advantages. It can be operated at relatively low electron beam energies (down to ~60 eV) and at room temperature. A major problem with an EBIT is how to inject the element of interest into the vacuum chamber, for spectroscopic or electron collision studies. For SH-permEBIT, it is difficult to use the methods of injecting elements into a traditional EBIT, such as metal-vapor vacuum arc and laser ion source, which can hardly be installed on it. Wire probes [4] and organometallic gases [3] have been successfully used to introduce metal elements into EBITs, but they are disadvantageous in that wire probes may destroy the electron beam shape and organometallic compounds may cause C/O contamination in the trap. For SH-permEBIT, organometallic compound condensation may even occur in the vacuum chamber when it is operated at the same temperature as the injection system, i.e. room temperature. Steady and continuous injection of simple substance is crucial for some experiments, and for wider applications of the SH-permEBIT, hence the development of a Knudsen Cell (K-CELL) injection system is required.

II. DEVICE SETUP

K-CELL is a high-temperature effusion cell working under fairly high vacuum conditions [5]. It has been widely used in molecular-beam-epitaxy (MBE) [6] experiments and in electron cyclotron-resonance ion source [7]. The Tokyo EBIT (traditional EBIT) has employed a K-CELL for metal vapor injection [8].

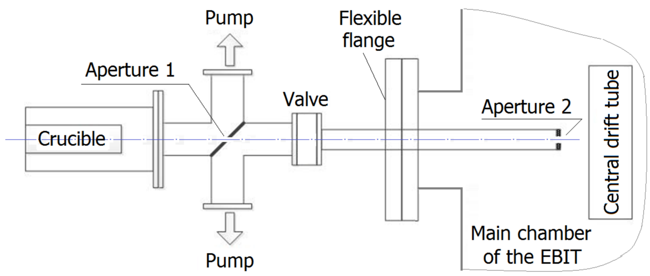

Fig. 1. Schematics of the K-CELL injection system. The valve keeps the vacuum of the main-chamber when the crucible needs to be charged or changed, and prevents it from contaminant gases of initial heating. The flexible flange is used for collimation.

Traditionally EBITs are operated at liquid helium temperatures with high vacuum in their drift tube region, while SH-permEBIT is operated at room temperature, hence a very different vacuum level in its drift tube region. So, modifications were made to accommodate for the operation conditions. As shown in Fig. 1, the K-CELL was fixed via a 4-way cross to the main body and central drift tube of the EBIT. A plate sloped at 45° containing a 1-mm aperture is installed in the centre of the cross. The K-CELL injection system is isolated from the EBIT by a vacuum valve, and a short vacuum pipe leads its way into the EBIT and ends at the central drift tube.

Aperture 1 in the 45° plate is used to confine diffused metallic vapor effusing out from the crucible. The vacuum between the two apertures is better than 10^{-6} Torr (1.3×10^{-4} Pa), and the mean free path of gas is over 50 m, being longer than the distance between the two apertures. So, after passing Aperture 1, the vacuum is high enough for metal atoms to go through the tube, or hit the wall of the vacuum line without collisions with other atoms. The valve keeps vacuum of the main-chamber when the K-CELL crucible needs to be charged or changed, and to prevent it from contaminant gases of initial heating of the K-CELL. The straight pipe, with a flexible flange connecting the EBIT, has a small aperture (Aperture 2) into the main-chamber and near the center drift

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tube (DT2), allowing the atomic beam to enter the drift tube region and cross with the electron beam. The drift tube has a 1 mm × 20 mm slit. Aperture 2 and the crucible of the K-CELL can be shifted by one or two millimeters by changing their support frames.

The K-CELL, four-way cross, valve and straight pipe line were assembled, making sure the crucible center and the two apertures were aligned (the K-CELL axis), and the whole injection system was installed on the EBIT, making use of the flexible flange to finally align the K-CELL axis and the slit on the same axis.

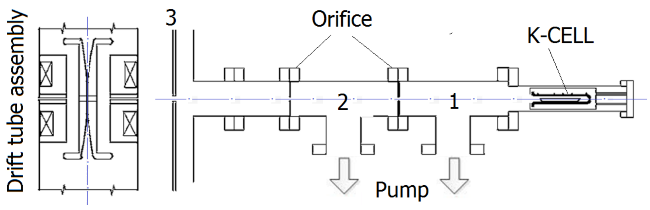

Fig. 2. Schematics of a traditional K-CELL injection system, from Tokyo EBIT [9]. A copy was made in our laboratory, but it did not work well. Our design, with a four-way cross with 45° sloped plate to replace the two three-way pipes (1 and 2), decreases transport loss in Sec. I. Our design has no third pipe and structure 3, so the final orifice can be placed near to the EBIT drift tubes, with reduced divergence of the atomic beam.

Compared to traditional schemes [9](Fig. 2), our design halved the transport distance of the effusing vapor from the crucible to Aperture 1. This drastically reduces the loss of effusing metallic atoms, according to the transport-residual formula [5]:

$$n_x = n_0 e^{-x/s}, \tag{1}$$

where n_x is number of residual atoms after a transport length of x, n_0 is total number of atoms effusing from the crucible, and s is mean-free-path of the vapor. Besides, Aperture 2 is placed near the slit of center drift tube, which reduces divergence of the atom beam and raises the injection efficiency, according to the injection rate formula [12]:

$$J = P(2\pi mkT)^{-1/2} \cdot e^{-x/s}\pi^{-1}l^{-2} \cdot S, \tag{2}$$

where J is the injection rate, P is pressure, m is atom's weight, k is Boltzmann constant, T is temperature in Kelvins, l is the length from crucible to the slit of DT2 and S is the aperture area.

The temperature was controlled by a Eurotherm 2408 Temperature Controller [14] with an accuracy of ±2 °C. The upper temperature limit of the K-CELL is 1400 °C according to the manufacture [15] and the vacuum is better than 10^{-3} Torr (0.13 Pa). It is often difficult, and unnecessary in some ways, to know the exact injection rate for a given element. Besides, the absolute strength of spectrum from EBITs depends on a number of factors, including vacuum of the EBIT chamber or residual gases from previous experiment. The injection pressure is usually set when a good spectrum of the injected element is obtained. Relative intensity of the spectrum, of an element injected into EBIT by traditional and improved K-CELL

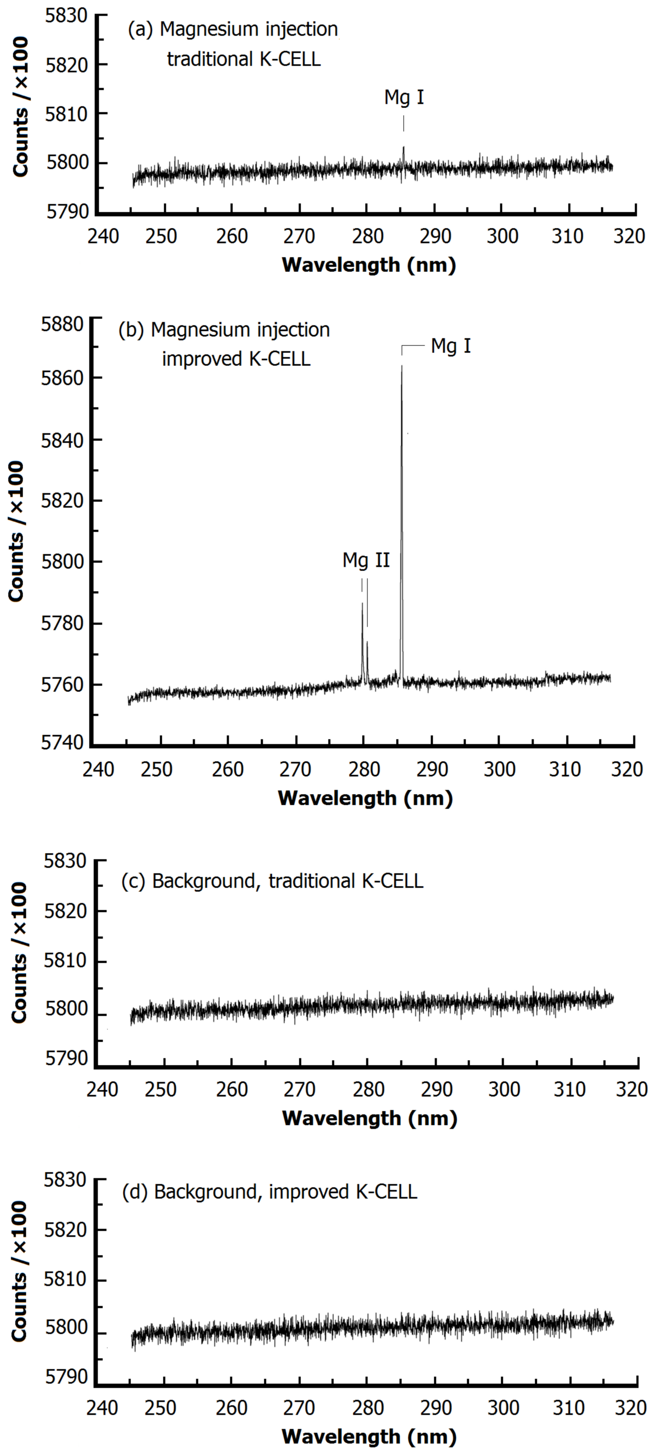

Fig. 3. Magnesium injection efficiencies of different schemes at 350 °C and 10^{-4} Torr of the crucible, with 730 eV electron beams of about 8.0 mA. The trap depth was 50 eV. The spectra were recorded for 1 hour by Andor (SR-303i) with 30 µm slit and 1200 l/mm grating blazed at 300 nm. With the traditional K-CELL, only a week Mg I line (285.21 nm) was recorded, while with the improved design, the Mg I line was much stronger and two Mg II lines (279.55 nm, 280.27 nm) were recorded clearly.

TABLE 1. The relationship between vapor pressure and temperature for ytterbium

Vapor pressure (Torr)	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
Temperature (°C)	247	279	317	365	417	482	557	647	787

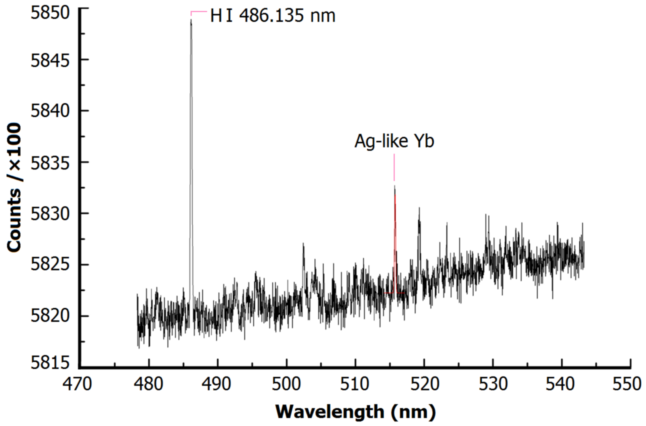

Fig. 4. Ag-like Yb M1 line at (5157.7 ± 1.0) Å in air, measured with 1100 eV E-beam at about 8.5 mA, and the trap depth of 200 eV. The K-CELL was operated at 400 °C.

injection systems under the same operating condition, would indicate our improvement. Efficiencies of magnesium injection into SH-PermEBIT by the two K-CELL injection system are shown in Fig. 3. The pressures in crucible were about 10^{-4} Torr (0.013 Pa) and electron beam energy was 730 eV. Only weak Mg I (285.21 nm) [16] signal was recorded with the traditional injection system, while strong Mg I and clear Mg II double line (279.55 nm, 280.27 nm) [16] were recorded with the improved K-CELL system.

III. EXPERIMENTAL

We contrived an experiment with the K-CELL injection system, trying to observe the $^2F_{7/2} \rightarrow {}^2F_{5/2}$ M1 transition line [11] in Ag-like Yb (Yb^{23+}). The temperature/vapor-pressure relationship for ytterbium is listed in Table 1 [13].

In this experiment, the crucible was heated to 400 °C, with the vapor pressure of nearly 10^{-4} Torr (0.013 Pa). The excited ions were produced and confined in the drift tube region, some of which decayed through emitting photons. The light was analyzed by a Czerny-Turner spectrometer from Andor (SR-303i), which covers wavelength range of 200–800 nm. To obtain a larger collection solid angle, we used a quartz lens of $f = 185$ mm between the EBIT window and the 30-µm entrance slit of spectrometer. Light from the center of drift tube was dispersed by a 1200 l/mm grating blazed at 300 nm and detected by a charge coupled device (Andor DU940P-BU2). The spectrum was recorded on the CCD-controlling computer. A typical spectrum is shown in Fig. 4. For the first time, we observed this M1 line. Analysis is on the way for future publications.

IV. CONCLUSION

In conclusion, the K-CELL injection system works well with the SH-permEBIT. This system can be used for injecting many metal or rare earth elements into SH-permEBIT, instead of using wire probes or organometallic gases. More experiments with the EBIT and K-CELL combination can be expected in the future.

[1] Zou Y and Hutton R. J Phys Conf Ser, 2007, **72**, 012003.
[2] Xiao J, Fei Z, Yang Y, *et al.* Rev Sci Instrum, 2012, **83**, 013303.
[3] Fei Z, Zhao R, Shi Z, *et al.* Phys Rev A, 2012, **86**, 062501.
[4] Elliot S R and Marrs R E. Nucl Instrum Methods Phys Res B, 1986, **57**, 1069–1084.
[5] Molecular Beam Epitaxy: Fundamentals and Current Status, Maria A. Herman, Springer-Verlag, 1996.
[6] Pardo R C and Billquist P J. Rev Sci Instrum, 1990, **61**, 239–241.
[7] Yamada C, Negata K, Nakamura N, *et al.* Rev Sci Instrum, 2006, **77**, 066110.
[8] Winterbottom W L and Hirth J P. J Chem Phys, 1962, **37**, 784–793.
[9] Nakamura N, Kinugawa T, Shimizu H, *et al.* Rev Sci Instrum, 2000, **71**, 684–686.
[10] Pardo R C and Billquist P J. Rev Sci Instrum, 1990, **61**, 239–241.
[11] Grumer J, Zhao R, Brage T, *et al.* arXiv:1405.2672.
[12] Winterbottom W L and Hirth J P. J Chem Phys, 1962, **37**, 784–793.
[13] Margrave J L. The Characterization of High-Temperature Vapors. New York (USA): John Wiley & Sons, Inc., 1967.
[14] http://www.eurotherm.co.uk/en-gb/products/controllers/single-loop/2400/2408/
[15] http://www.hx-vac.cn/product_6.html
[16] Kramida A, Ralchenko Yu, Reader J, *et al.* NIST Atomic Spectra Database (ver. 5.1). http://physics.nist.gov/asd